SS 433: Radio/X-ray anti-correlation and fast-time variability

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Abstract. We briefly review the Galactic microquasar SS 433/W50 and present a new RXTE spectral and timing study. We show that the X-ray flux decreases during radio flares, a behavior seen in other microquasars. We also find short time-scale variability unveiling emission regions from within the binary system.

1. SS433/W50 Review

SS 433 is the famous galactic microquasar known by its two-sided precessing mildly relativistic (0.26c) jets (Margon 1984). The question whether the compact object is a neutron star or a black hole remains unanswered, in spite of its discovery over 2 decades ago. ASCA observations revealed Doppler blue- and red-shifted emission lines (Kotani et al. 1996) indicating a jets' scale of $\sim 10^{13}$ cm. Recent Chandra observations with the gratings (Marshall et al. 2002) gave a mass outflow rate of 1.5×10^{-7} $M_\odot$ yr^{-1} and a kinetic power of 3.2×10^{38} erg s^{-1} (at an assumed distance of 4.85 kpc). The latter values are small compared to previous estimates of $\sim 10^{-6}$ $M_\odot$ yr^{-1} and 10^{39}-10^{41} erg s^{-1} (possibly because SS 433 was in a low state during the Chandra observations).

SS 433 is near the center of the supernova remnant (SNR) W50. Observations in the radio (Dubner et al. 1998), millimeter (Durouchoux *et al.* 2000; Sood *et al.* 2002 in preparation), infrared (Fuchs, Koch-Miramond, & Abraham 2001), optical (Mazeh *et al.* 1983), and X-rays (Safi-Harb & Petre 1999 and refs therein) show that the SS 433 jets are interacting with the surounding inhomogeneous medium, causing the unusual morphology and the X-ray lobes of W50.

SS 433 was observed by the RXTE at several occasions. Here we present the preliminary results of our spectral and timing study. A more detailed analysis and interpretation of our results will be presented elsewhere. We also refer the reader to a companion paper (Kotani *et al.* this volume) highlighting the multiwavelength 2001 campaign, and to several other SS 433 papers in this volume highlighting the most recent multi-wavelength observations: Namiki *et al.* for recent Chandra observations, Fabrika *et al.* for the optical observations, Fuchs *et al.* for the infrared observations suggesting a Wolf-Rayet star origin, Blundell *et al.* and Paragi *et al.* for the evidence of an equatorial outflow, Migliari *et al.* for thermal reheating in the jet, Trushkin *et al.* for the 6-day modulation in the quite radio emission, and Chakrabarti *et al.* for the theoretical implications.

2. Radio and X-ray anti-correlation

RXTE observed SS 433 in 1996 (ϕ=0.83–1.12; ψ=0.78–0.81), 1998 (ϕ=0.01–1.0; ψ=0.1–0.2), and 2001 (ϕ=0.1–1.3; ψ=0.29–0.38); where ϕ and ψ are the optical and precession phases, respectively. A radio flare occurred mid March 1998 (around MJD 50890) and in November 2001 (MJD 52215 and 52235), as shown in Fig. 1 by the arrows. Luckily the 1998 flare (detected with the NRAO GBI) was covered by two short RXTE observations, and the November 2001 flare detected with the RATAN 600-m telescope (Kotani & Trushkin 2001) was monitored by RXTE for 2 weeks (except for November 18, 2001).

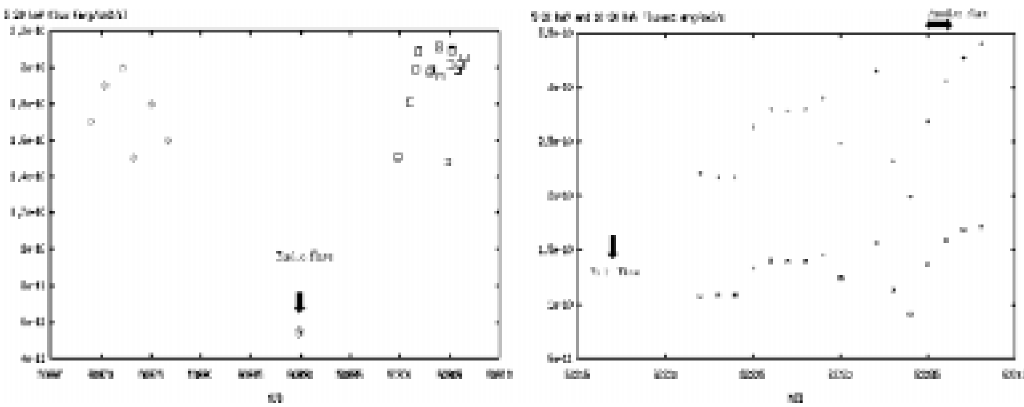

Figure 1. The hard X-ray PCA fluxes of SS 433 in 1998 and 2001.

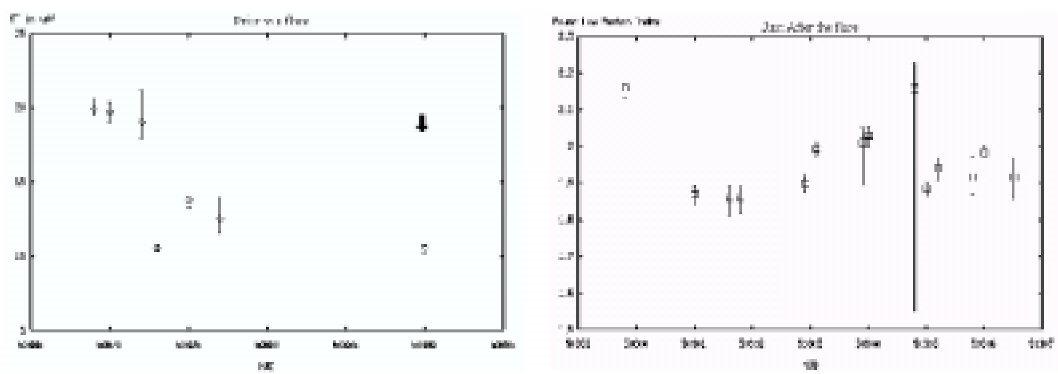

Figure 2. The thermal bremsstrahlung temperature (kT) and power law photon index (Γ) for the 1998 observations. The arrow in the left panel shows the radio flare (MJD 50890).

The PCA spectra are well fitted with a thermal bremsstrahlung model (or a power law model at occasions, see below), modified by interstellar absorption, and with two Fe-lines: A broad line and a narrow line. In Fig. 1, we show the hard X-ray flux variations and its anti-correlation with the radio flares that occurred in 1998 (left) and 2001 (right). In Fig. 2, we show the variations of the spectral parameters, kT and Γ, fixing N_H at 0.7×10^{22} cm^{-2}. We find that 1) the X-ray flux decreases during the flare, 2) the spectrum softens at the onset of the flare then hardens shortly after, and 3) the spectrum switches from thermal to power law right after the flare in 1998. The narrow line variations (believed to originate from the jets) are also consistent with the redshifts or blueshifts determined from optical spectroscopy (Kotani *et al.* 2002).

3. Fast time variability

Previous observations revealed no variability on time-scales shorter than 300 s. A search for variability in the 0.5-300 s range in the ROSAT data (Safi-Harb 1997, see Fig. 3, left) using the method of autocorrelation function shows flickering around 3–10 s. However, this variability does not appear consistently in all the observation segments, and the time scale varies from an observation segment to the other. Using the PCA Nov. 2001 data, we also found fast time variability (Fig.3, right), which we confirmed using previous archival PCA observations. The time scale of 50–100 s indicates a length scale $\leq 10^{12}$cm. Fast time variability is expected when the source enters a highly non-stationary regime expected from super-critical accretion into the surface of a neutron star.

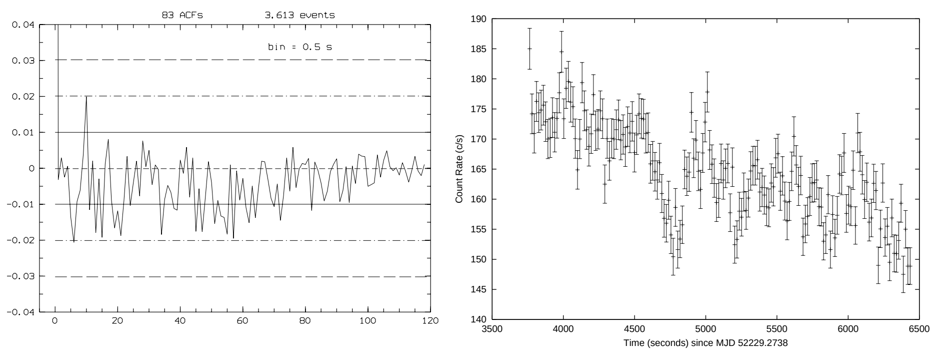

Figure 3. (Left): Autocorrelation function of a ROSAT observation. The solid, dash-dotted and dotted lines are 1σ, 2σ, and 3σ levels for a random distribution. A periodic signal would manifest itself as a local maximum. (Right): RXTE light curve of an observation obtained in Nov. 2001.

4. Progress and the future

We have presented the first evidence for the hard X-ray/radio anti-correlation, and for fast time variability. The spectral behavior mimics the behavior seen in other microquasars (Mirabel & Rodriguez 1999). The short time scales indicate that we are, for the first time, probing the high-energy emission regions closer to the compact object. Chakrabarti et al. (2002) show that non-steady shocks in sub-Keplerian accretion flow provides the basic timescale of the ejection interval.

SS 433 remains unique compared to other microquasars: 1) the ratio of its X-ray flux to the jets power is much smaller (10^{-4} compared to 0.1 for GRS 1915+105), 2) it's the only microquasar with large scale X-ray and radio lobes resulting from the interaction between the jets and the surrounding medium/SNR (see however the discovery by Corbel et al., this volume, of large scale jets from a black hole), and 3) it's the only source confirmed to have precessing jets with Doppler shifted emission lines revealing a complex system with baryonic jet matter. The current picture that best explains the properties of this enigmatic object is a binary system embedded in an expanding thick disk that is fed by the wind from a super-Eddington accretion rate (see Gies et al. 2002). The companion star is most likely a Wolf-Rayet star dumping some 10^{-4} $M_{\odot}$ yr^{-1} into the compact object. This would explain the large infrared flux, the low X-ray luminosity, and the difficulty to detect any pulsations.

Several burning questions still need to be addressed with further observations: 1) the discrepancy in the distance derived for SS 433 and W50 needs also to be resolved to derive better estimates for the mass outflow and the jets power; 2) the nature of the compact object remains ambiguous. While the majority of published papers point to an underlying black hole (e.g. Zwitter & Calvani 1989), a later estimate by D'Odorico *et al.* (1991) indicates a neutron star origin. Interestingly, even in the latter scenario, the neutron star's mass is unusually low. If the estimated mass is indeed 0.8±0.1 $M_{\odot}$, then SS 433 would join the growing class of low-mass 'neutron' stars (Gondek-Rosinska, Kluzniak, & Stergioulas 2002).

SS 433 remains unique. While other objects have been claimed to be SS 433-like (see reviews in this volume by Safi-Harb, Fender, and the study of CI-Cam and V4641 Sgr by Rupen), none of them is an SS 433–twin. SNRs offer a promising laboratory to search for binary compact objects (potential SS 433's). Simultaneous monitoring of SS 433 in the radio, infrared, high energy X-rays and gamma-rays is needed to study in more detail the spectral and timing behavior discussed here, in comparison with other microquasars. Most importantly, a reliable estimate of the mass function will hopefully solve a 25-year old puzzle.

Acknowledgments

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